

High reddening patches in *Gaia* DR2

Possible artifacts or indication of star formation at the edge of the Galactic disk

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ABSTRACT

Context. Deep GALEX UV data show that the extreme outskirts of some spiral galaxies are teeming with star formation. Such young stellar populations evolving so far away from the bulk of their host galaxies challenge our overall understanding of how star formation proceeds at galactic scales. It is at present unclear whether our own Milky Way may also exhibit ongoing and recent star formation beyond the conventional edge of the disk (~ 15 kpc).

Aims. Using *Gaia* DR2 data, we aim to determine if such a population is present in the Galactic halo, beyond the nominal radius of the Milky Way disk.

Methods. We studied the kinematics of *Gaia* DR2 sources with parallax values between 1/60 and 1/30 milliarcseconds towards two regions that show abnormally high values of extinction and reddening; the results are compared with predictions from GALAXIA Galactic model. We also plotted the color–magnitude (CM) diagrams with heliocentric distances computed inverting the parallaxes, and studied the effects of the large parallax errors by Monte Carlo sampling.

Results. The kinematics point towards a Galactic origin for one of the regions, while the provenance of the stars in the other is not clear. A spectroscopic analysis of some of the sources in the first region confirms that they are located in the halo. The CM diagram of the sources suggests that some of them are young.

Key words. Galaxy: stellar content – Galaxy: halo – Galaxy: structure – Galaxy: evolution

1. Introduction

It has been customarily assumed that star formation cannot proceed within low gas density environments, such as those that characterize the outermost regions of galactic disks (Ferguson 2002; Bianchi 2009). However, the Galaxy Ultraviolet Explorer (GALEX, Martin et al. 2005) revealed the presence of young stellar populations in the extreme outskirts of spiral galaxies, well beyond where the bulk of the galactic-scale star formation was assumed to take place (Bianchi et al. 2005; Thilker et al. 2005, 2007). A common feature of all these galaxies is that they lie in groups, as do most of the galaxies in the Local Universe, including the Milky Way, and hence extended ultraviolet emission could be a natural consequence (Marino et al. 2010). Nevertheless, the presence of young massive stars in the outskirts of our Galaxy is very difficult to confirm in the ultraviolet range because of the high extinction areas close to the Galactic plane (Schultheis et al. 2015; Schlafly et al. 2016, 2017). It is therefore necessary to follow an alternative approach and look for young stars in other spectral ranges.

With the second data release of the *Gaia* mission (*Gaia* DR2, Gaia Collaboration 2016, 2018a), an extensive database of astrometric measurements for sources up to 90 kiloparsecs (kpc) from the solar system, including proper motions, radial velocity, and photometry in blue G_{BP} , red G_{RP} , and green G passbands, together with extinction A_G and reddening $E(G_{BP} - G_{RP})$, is now available. This unique database provides a refined characterization of the structure and evolution of the Milky Way (Gaia Collaboration 2018b; Helmi et al. 2018; Antoja et al.

2018) and could provide useful data for the search of very young stars in the halo region, beyond the nominal edge of the disk (15 kpc from the Galactic center, Armentrout et al. 2017). In this work we present our efforts to search for recent star formation in the outskirts of the Milky Way using *Gaia* DR2 data. The sample selection is explained in Sect. 2, the kinematics of the potentially young candidates are studied in Sect. 3, and a discussion of the results is presented in Sect. 4. Finally, the main conclusions of our work are summarized in Section 5.

2. Sample

Young stars are characterized by their strong ultraviolet emission. However, since in the early phases of stellar evolution they are still embedded in a dust dense envelope, light at ultraviolet and optical wavelengths is attenuated. In addition, if they are far away, the presence of interstellar clouds in the lines of sight to stars contributes to the overall extinction and an apparent redder color is observed. We do not expect to be able to resolve stars of the first type in the outskirts of the Milky Way because they will be severely extinguished and their detection unfeasible. Nevertheless, we can try to find distant young stars, of a few hundred Myr¹, that will be naturally reddened by the interstellar material of the disk.

¹ Hereafter, when we refer to young stars we mean stars with an age of ~ 100 – 200 Myr, independently of the evolutionary stage.

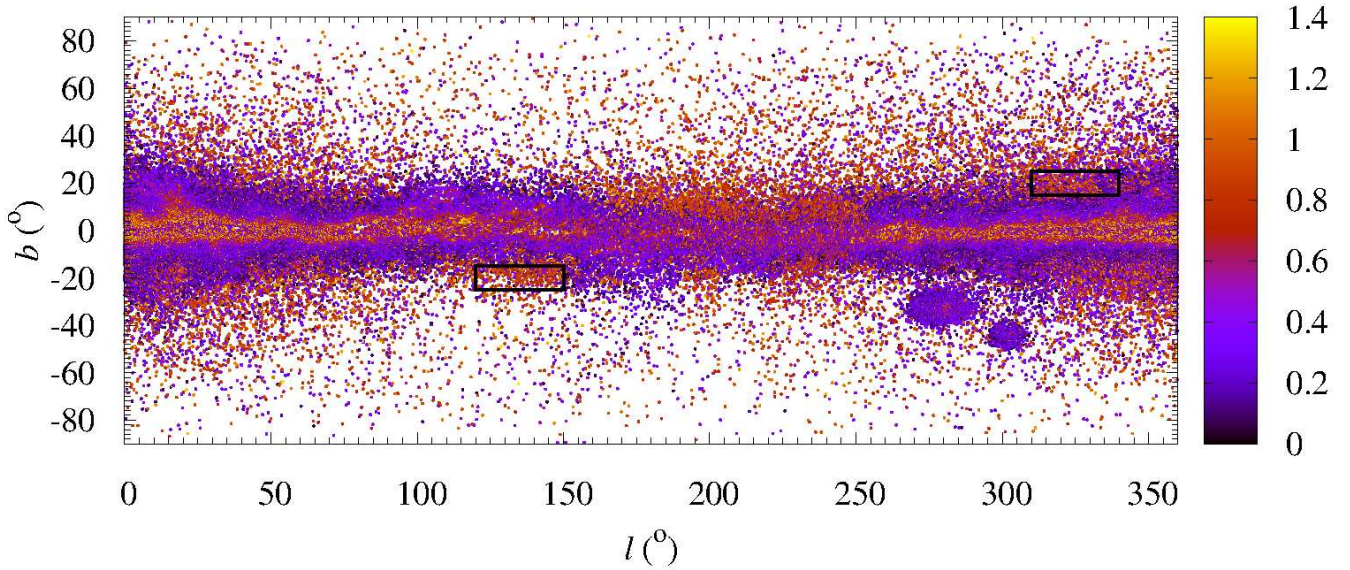


Fig. 1. Reddening map for distant sources in Galactic coordinates. Scatter plot of all *Gaia* DR2 sources with parallaxes between 1/60 and 1/30 mas (nominal heliocentric distances between 30 and 60 kpc) in Galactic coordinates. The color-coding corresponds to the value of the reddening, $E(G_{BP} - G_{RP})$. The black rectangles enclose Region 1 (*lower left*) and Region 4 (*upper right*).

Keeping these ideas in mind, we searched for stars with unusually high reddening values in the vast database of *Gaia* DR2.

We selected all the stars with strictly positive values of parallax and non-null values of reddening $E(G_{BP} - G_{RP})$ derived by the Apsis data processing pipeline (Andrae et al. 2018), resulting in a catalogue of 87 733 672 stars.

First, we plotted all the stars in slices of a few hundred parsecs estimating the distance as the inverse of the parallax and examined *Gaia* DR2 data in search of regions with unusual patterns of reddening. The most interesting results were found at parallax values between 1/60 and 1/30 milliarcseconds (mas), which would ideally correspond to distances in the range 30–60 kpc, so we focused our attention on this subsample. In addition, these *Gaia* DR2 sources were systematically ignored in previous studies because of the extremely large parallax errors, usually on the order of the parallax value itself. In this way our study can be considered both a search for a young population in the Milky Way halo and an independent assessment of the reliability of extreme *Gaia* DR2 measurements. For stars with parallax values between 1/60 and 1/30 mas, we searched for regions detached from the Galactic disk (Galactic latitudes $|b| > 15^\circ$) where a moderate number of extinguished sources with reddening greater than 0.8 are present. We identified four regions that meet these requirements (see Fig. 1); we labeled them Region 1 ($l, b = (135^\circ, -20^\circ)$), Region 2 ($l, b = (195^\circ, -15^\circ)$), Region 3 ($l, b = (230^\circ, -20^\circ)$), and Region 4 ($l, b = (325^\circ, +20^\circ)$). From these four overdensities we selected Regions 1 and 4 because they are significantly redder than their mirror Galactic counterparts (same longitude, opposite latitude; see Fig. 2).

Since the parallax errors are extremely large, if we apply any cut based on them the resulting sample will be practically nonexistent. On the other hand, we can use the renormalized unit weight error (RUWE) measurement associated with each *Gaia* DR2 source to determine the quality and reliability of the astrometric parameters (see *Gaia* Collaboration 2018a; Lindegren 2018, for details). Basically the RUWE value indicates whether the derived parameters for the source are reliable or if there are any problems with the astrometric solution. For

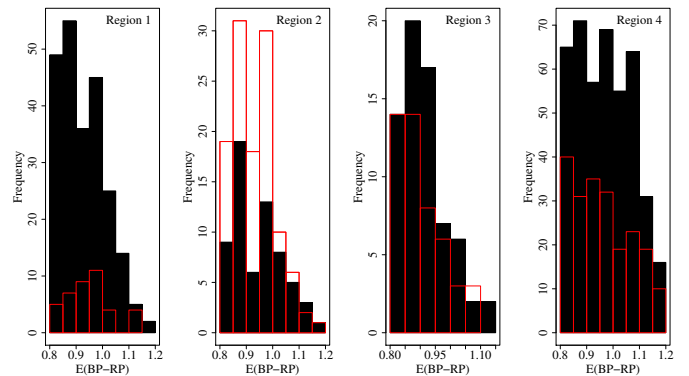


Fig. 2. Distribution of sources with reddening values between 0.8 and 1.2 towards the four Regions discussed in Section 2 in black, and their mirror Galactic counterparts (same longitude, opposite latitude) in red.

the stars in our sample, the RUWE value is less than 1.4 for more than 95% of the objects, meaning that their astrometric solution is valid. We also did not apply the zero-point correction since it is discouraged by Lindegren et al. (2018) and there are serious discrepancies in the exact value (see, e.g., the discussion in de la Fuente Marcos & de la Fuente Marcos 2019, and references therein). In addition, it is not clear how our regions might be affected, and the correction value is the same order of magnitude as the parallaxes. However, we were able to confirm independently that some of them are actually that far away (see Sect. 4).

We note that contamination may arise from the Galactic disk but also from stellar and Galactic streams. Towards Region 1 and at heliocentric distances of ~ 18 –20 kpc lies the Triangulum-Andromeda (TriAnd) overdensity (Bergemann et al. 2018; Hayes et al. 2018), which according to recent studies has an origin in the Milky Way disk, but whose stars have ages ranging from 6 to 10 Gyr (Bergemann et al. 2018); there is no known stellar stream or overdensity associated with Region 4. In both cases, the peculiar stellar population seems to be well detached from the bulk of the disk population (see Fig. 1).

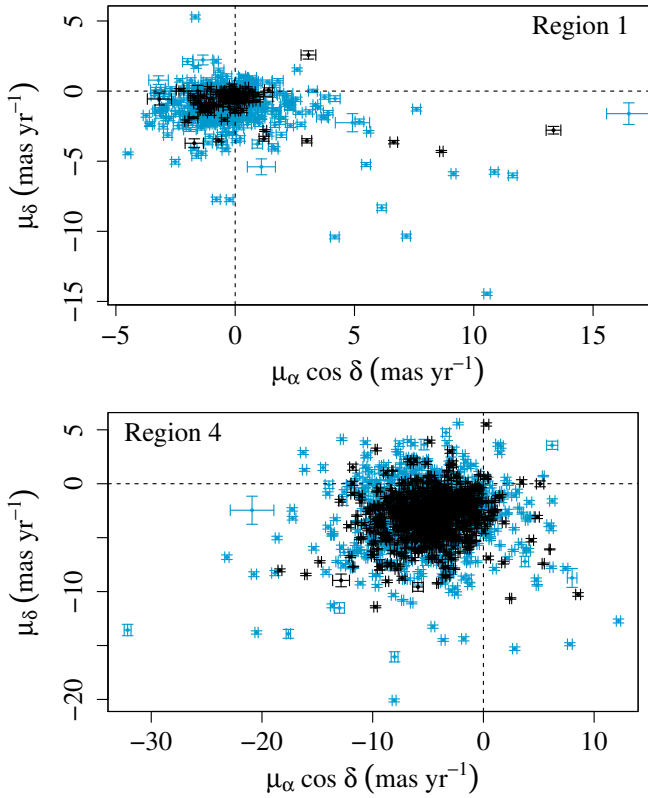


Fig. 3. Proper motions of *Gaia* DR2 sources in Region 1 and Region 4. Blue points (376 in Region 1; 741 in Region 4) correspond to sources with values of $G_{BP} - G_{RP} < 0.5$, while black points (83 in Region 1; 690 in Region 4) correspond to sources with $G_{BP} - G_{RP} > 0.5$.

3. Kinematics

Motivated by the high values of reddening of our stars in *Gaia* DR2, we studied their kinematics in order to search for evidence of internal coherence. As we want to determine if they were formed inside the Milky Way or, on the other hand, are part of an external stellar stream, we compared the data with synthetic data from the Galactic model GALAXIA (Sharma et al. 2011), which takes into account the warp and flare of the disk.

First, we studied the proper motions of both regions, which are displayed in Fig. 3. In the analysis, we distinguished between sources with color $(G_{BP} - G_{RP}) - E(G_{BP} - G_{RP}) < 0.5$ (blue points) and > 0.5 (black points) since we expected that any young stellar candidates would lie within the blue population. For an A7V star, $B - R = 0.5$ is the turnoff point of a 165 Myr old metal-rich cluster, so it makes sense to assign this arbitrary boundary when looking for relatively young populations and it is also consistent with our own definition of youth (see, e.g., Howell et al. 2005). Although we observe that there is no apparent difference between the black and blue populations (see Table 1), stars in Region 4 are far more dispersed and their proper motions are five times higher than those in Region 1.

The key parameter left to fully determine the kinematics of the populations is the radial velocity. Unfortunately, *Gaia* DR2 only provides measurements for 13 sources in Region 1; for Region 4 we have a statistically more significant sample including 51 stars. Due to the scarcity of available data, we performed a very simple, non-parametric statistical study based on the median value of radial velocity given by the GALAXIA model

Table 1. Median and interquartile range (IQR) values in mas yr^{-1} for the proper motions of stars in Regions 1 and 4.

	Region 1		Region 4	
	Blue points	Black points	Blue points	Black points
$\mu_\alpha \cos \delta$ – median	−0.594	−0.300	−5.018	−4.560
IQR	1.772	1.277	4.977	3.496
μ_δ – median	−1.029	−0.551	−2.607	−2.715
IQR	1.569	0.927	3.593	2.421

Table 2. Radial velocity statistics (in km s^{-1}) for the sources in the regions of interest.

	Data		Model – disk		Model – halo	
	Median	IQR	Median	IQR	Median	IQR
Region 1	−89	39	−26	50	−132	149
Region 4	31	173	−31	74	106	164

and the data, and the interquartile range (IQR)². The results are summarized in Table 2 and complementary histograms are shown in Fig. 4. Although the IQRs are wide, it is clear that at least Region 1 shows an anomalous distribution in radial velocities, while Region 4 data could suffer from disk contamination.

Finally, for the samples with radial velocity, we computed the heliocentric Galactic velocities UVW following the standard procedure (see, e.g., Johnson & Soderblom 1987) and compared them with predictions from GALAXIA (Fig. 5); the associated errors were also computed, but are not displayed due to the extremely large uncertainties. From these plots we interpret that Region 1 data are compatible with a Galactic origin, perhaps due to a possible contamination arising from TriAnd, while the trends in Region 4 indicate that these sources were not born in the place where they are observed now. What we conclude in view of the very different kinematics is that these two regions do not share a common origin.

The Galactic orbits of stars in *Gaia* DR2 with full data sets (i.e., also including radial velocity) can be estimated using Galpy (Bovy 2015). For those stars in Regions 1 and 4 with complete kinematic information (13 and 52 sources, respectively), we computed the orbital motions by applying Monte Carlo sampling. We generated 10^4 instances of the input data set required to calculate one orbit using values and uncertainties from *Gaia* DR2, then extracted relevant parameters such as the maximum value of the Z coordinate (Z_{max}) and the eccentricity (e). For each source and using the 10^4 orbital realizations, we computed median values and the 16th and 84th percentiles to estimate the uncertainties, as we describe in the previous sections. The orbits were calculated using the gravitational potential recommended in the Galpy documentation, MWPotential2014 (Bovy 2015), which includes a bulge, a disk, and a dark matter halo component, but neither spiral arms nor giant molecular clouds. Our results are shown in Fig. 6. Most sources are fully consistent with halo membership, but the samples from Regions 1 and 4 clearly have different provenance. The sample in Region 4, if located as far away as the data suggest, might not have an origin in the Milky Way. A possible formation scenario

² The IQR is a measure of statistical dispersion that indicates the width of the interval where 50% of the data are included.

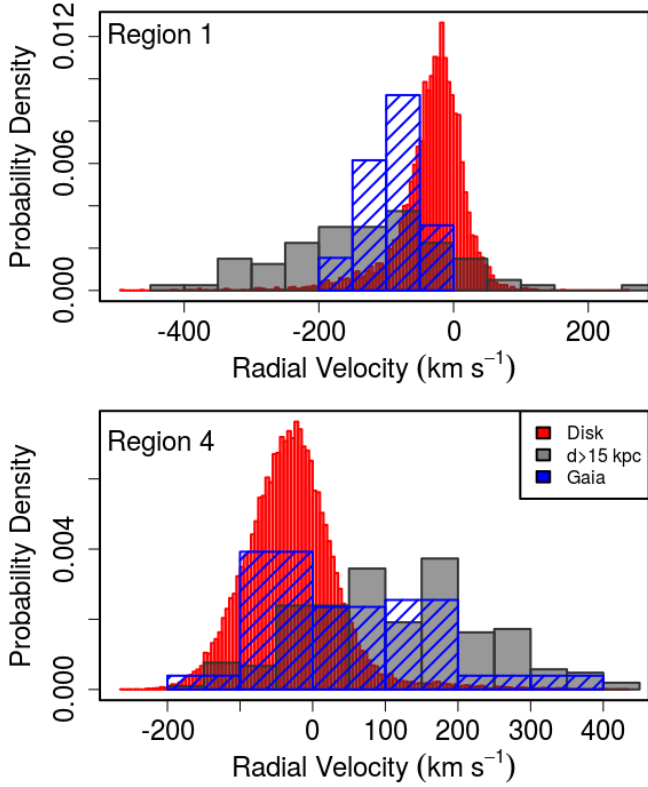


Fig. 4. Histogram of radial velocities of sources from Regions 1 and 4. Red bars correspond to GALAXIA predictions for the disk of the Milky Way, while gray bars correspond to predictions for the halo; blue dashed bars correspond to probability densities of *Gaia* DR2 data (13 sources in Region 1; 51 in Region 4). The probability density is an amount such that the sum of the values times the bin size is equal to 1. Bins were computed according to the Freedman–Diaconis rule.

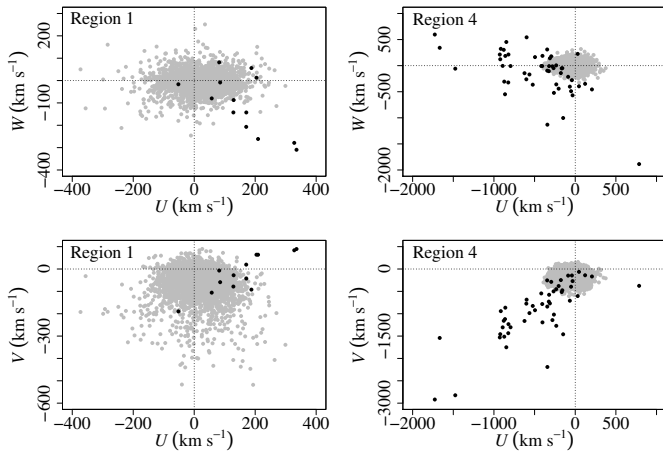


Fig. 5. Heliocentric velocities for sources towards Regions 1 and 4. Gray dots are GALAXIA predictions (7065 in Region 1; 26031 in Region 4), black dots are *Gaia* DR2 sources with radial velocity data (13 in Region 1; 51 in Region 4).

for these stars would be the collision of a high velocity cloud with the disk (Eggen et al. 1962).

4. Discussion

In the first approach, we plotted the CM diagram for Regions 1 and 4, taking *Gaia* DR2 parallax, extinction, and reddening

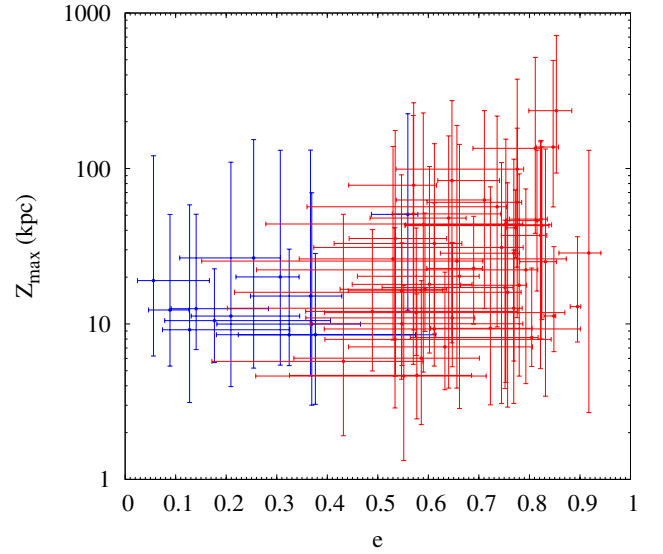


Fig. 6. Galactic orbits characteristic of sources in Regions 1 and 4. Maximum height above the plane of the orbit as a function of the eccentricity for relevant sources in Region 1 (13, in blue) and Region 4 (52, in red). Median values and error bars displaying the 16th and 84th percentiles are shown.

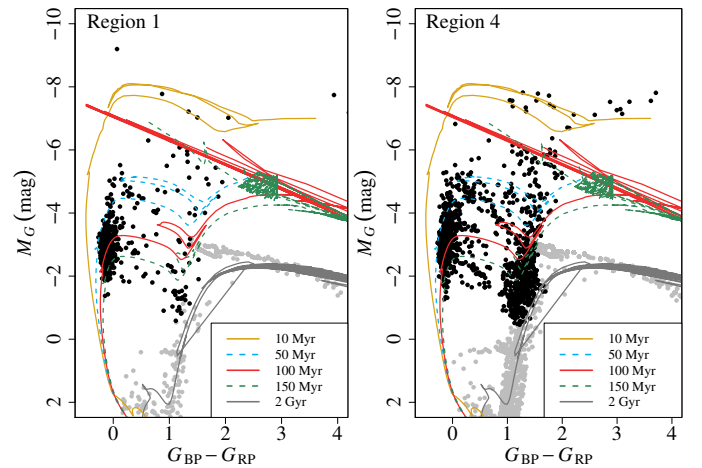


Fig. 7. Color-magnitude diagrams for Regions 1 and 4 for *Gaia* DR2 data, corrected from extinction and reddening and with distance estimated inverting the nominal parallax; for comparison, GALAXIA predictions are shown as gray dots. Shown are (from top to bottom) PARSEC+COLIBRI PR 16 isochrones with solar metallicity of 10 Myr (gold line), 50 Myr (dashed blue line), 100 Myr (solid red line), 150 Myr (dashed green line), and 2 Gyr (solid gray line).

values; the results are displayed in Fig. 7 with some overlaid PARSEC+COLIBRI PR16 isochrones of solar metallicity (Marigo et al. 2017; Bressan et al. 2012) and GALAXIA predictions. In both cases the data suggest the presence of a blue population that is evolving towards the red branch of the diagram, much younger than the current ~ 2 Gyr population already known and predicted by the models. However, while the errors in apparent magnitudes are not significant, the errors in the parallax are considerable. The most suggested line of action in these cases is to apply Bayesian inference to predict distances from the parallaxes (Luri et al. 2018; Bailer-Jones et al. 2018), but due to the large uncertainties, the posterior distribution will be strongly affected by the prior, and hence the predicted distances will be

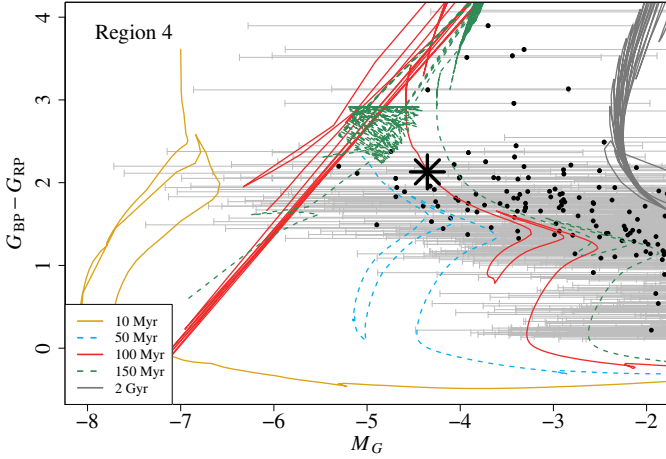


Fig. 8. Zoom-in of the color-magnitude diagram for Region 4 after applying the Monte Carlo sampling. For better illustration, the axes have been rotated and the error bars are displayed in gray. The big black star is one of the most promising young star candidates, *Gaia* DR2 6116708946261654272, because of the bounded errors in absolute magnitude (no additional information in Vizier has been found).

shorter than they really are. Instead, we followed the approach outlined by [de la Fuente Marcos & de la Fuente Marcos \(2019\)](#) and estimated the heliocentric and Galactocentric distances via Monte Carlo sampling, assuming a distance to the Galactic Center of $d = 8.18$ kpc ([Abuter 2019](#)); for each source, we performed 10^5 Monte Carlo simulations. Since *Gaia* DR2 values for extinction and reddening were derived neglecting the parallax uncertainties ([Andrae et al. 2018](#)), we determined the absolute magnitudes solely from our Monte Carlo parallaxes. Figure 8 shows the sources of Region 4 for which the Monte Carlo estimates are compatible with a young age, although it is clear that the errors in the parallaxes are so large that we cannot be certain about the values. The most promising candidate in Region 4 is *Gaia* DR2 6116708946261654272, with lower bar error in absolute magnitude $M_G < -3$ and 16th Galactocentric distance percentile³ greater than 15 kpc. Thus, we performed an extensive search in both Vizier⁴ ([Ochsenbein et al. 2000](#)) and SIMBAD ([Wenger et al. 2000](#)) looking for any available information about the samples that could shed some light on the question of their age. What we found is that in general, there is not much information about sources in Region 4, which we ascribe to their location in the southern celestial hemisphere, while for sources in Region 1 there are some LAMOST DR4⁵ ([Luo et al. 2018](#)) spectra available that we used for the purpose of estimating spectroscopic parallaxes. Eventually, we found one star, *Gaia* DR2 375075920547984000, which is classified as an A2IV by LAMOST DR4. We estimated the Galactocentric distance to the source spectroscopically and via Monte Carlo sampling, and the results are compatible. For the spectroscopic estimate, we took YZ Cassiopeiae as an A2IV reference star, with a visual magnitude $M_V = 0.251$ mag ([Bilir et al. 2008](#)), and we obtained a heliocentric distance of 21.2 kpc with an estimated

error of 0.9 kpc⁶, which corresponds to a Galactocentric distance of 26.3 kpc for this object; the Monte Carlo estimates are compatible with a median Galactocentric distance of 17.5 kpc, and percentiles $p_{16} = 11.1$ kpc and $p_{84} = 49.6$ kpc. This star is also included in the Starhorse catalog recently published by [Anders et al. \(2019\)](#) although the distance estimate is not very reliable; the resulting distance probability density function is very broad. Nevertheless, their Galactocentric distance is also compatible with our results, with a value of 26.3 kpc. In summary, we have an A2IV star located farther than 15 kpc from the Galactic center. This star is very likely to be young since an A2 star spends little time in the subgiant stage, and in consequence there should be more young stars with it, unless it is a runaway star (see, e.g., [Hoogerwerf et al. 2000](#)); no conclusions can be drawn without a better characterization of the star (radial velocity, reddening, and precise parallax).

To determine whether there are more young star candidates like the one just discussed, we need to be sure that *Gaia* DR2 nominal parallaxes are valid despite the large errors. Our search in Vizier has reported two more encouraging results. *Gaia* DR2 396558526625729152 is classified in LAMOST DR4 as an A2V that gives a spectroscopic Galactocentric distance of 17.4 kpc (taking $M_V = 1.3$ mag, [Drilling & Landolt 2000](#)), and *Gaia* DR2 338768431691725824 is an RR Lyrae star ([Sesar et al. 2017](#)) with a distance modulus of 16.31 mag. Although the RR Lyrae is not a young star, both of them are well beyond the nominal edge of the Galactic disk. We are thus convinced that *Gaia* DR2 parallaxes for distant sources are more reliable than previously thought.

However, there could be some contamination arising from TriAnd suggested by the presence of two stars in Region 1, *Gaia* DR2 374544482769997056 and *Gaia* DR2 330307728370143360, that were previously identified by [Sheffield et al. \(2014\)](#) as bona fide members of TriAnd. In addition, an old population is clearly revealed by LAMOST: *Gaia* DR2 339458031639126016 is classified as a M1 star, and *Gaia* DR2 388342971445046272 as a K7. The list of the discussed stars is shown in Table 3.

5. Conclusions

If we take into account the analysis presented in the previous section, we are convinced that nominal *Gaia* DR2 parallaxes may be valid even for very distant sources ($d > 15$ kpc), since our Monte Carlo estimated values are always compatible with the few spectroscopic estimates available. Nevertheless, the topic of the age of the sources is still debatable. In view of the corrected data shown in the CMD in Fig. 8, and assuming (based on the few confirmed cases) that most of the stars are really that far away, we conclude that within the samples there must be some young stars, the most promising candidate being *Gaia* DR2 375075920547984000. On the other hand, although the stars are likely to be distant, they are not located farther than 30 kpc, meaning that the errors in the parallax are not negligible. Hence, reddening and extinction values derived by Apsis are likely to change, and we have to be cautious with respect to the CMD and the results that can be drawn from them. We are hopeful that with the arrival of *Gaia* DR3 we will be able to select a reliable sample of candidates in both regions to be studied in more detail.

⁶ We used LAMOST g and r magnitudes for the estimation of the V magnitude via the relationship $V = r + 0.44(g - r) - 0.02$, considering an error of 0.05 mag for each magnitude.

³ We computed the 16th (p_{16}) and 84th (p_{84}) percentiles following Apsis convention. They can be considered asymmetric error bars for the median estimates.

⁴ All the matches in Vizier were carried out in a search radius of $3''$.

⁵ <http://dr4.lamost.org/>

Table 3. Stars with additional data discussed in Sect. 4.

Star	Other IDs	Notes	Reference
<i>Gaia</i> DR2 375075920547984000	LAMOST DR4 197116019	A2IV	Luo et al. (2018)
<i>Gaia</i> DR2 396558526625729152	LAMOST DR4 370404083	A2V	Luo et al. (2018)
<i>Gaia</i> DR2 338768431691725824		RR Lyrae	Sesar et al. (2017)
<i>Gaia</i> DR2 374544482769997056		TriAnd member	Sheffield et al. (2014)
<i>Gaia</i> DR2 330307728370143360		TriAnd member	Sheffield et al. (2014)
<i>Gaia</i> DR2 339458031639126016	LAMOST DR4 191606221	M1	Luo et al. (2018)
<i>Gaia</i> DR2 388342971445046272	LAMOST DR4 164415092	K7	Luo et al. (2018)

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